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Distortion Analysis of Magnetic Excitation – Inherent reflection of properties of ferromagnetic materials

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Abstract

This letter briefly presents an interesting set of results from a non-destructive magnetic measurement method named as the Distortion Analysis of Magnetic Excitation (DAME). The time derivative of the excitation voltage (V_E) across the coil around the electromagnetic (EM) yoke plotted as a function of total applied voltage (V_T) (named as the DAME profile) truly reflects the magnetisation behaviour of the ferromagnetic material introduced between the poles of the EM yoke to close the magnetic flux path. The shape of the DAME profile with a peak and trough clearly reflects the subtle changes in the composition, microstructure, grain orientation and stress through their effect on the magnetisation process in the ferromagnetic material placed between the poles of the EM yoke. This letter shows that the DAME profile measurement is a simple non-destructive evaluation (NDE) method to detect and determine variations in the properties of ferromagnetic materials and has tremendous potential for several applications related to the evaluation of ferromagnetic materials and components.

Keywords: Distortion analysis, magnetic excitation, microstructure, grain orientation, stress

1. Introduction

Magnetic measurements such as B-H loop and magnetic Barkhausen noise (MBN) are well known to researchers studying characterisation of ferromagnetic materials. Distortion of magnetic parameters is known to be influenced by properties of ferromagnetic alloys. Distortion of B-H loop has been studied using harmonic analysis of magnetic induction [1-3] and harmonic analysis of tangential magnetic field strength has been studied using distortion factor [4,5] for correlation of material properties. However, the distortion behaviour of the excitation voltage across the coil around an electromagnetic (EM) yoke, the fundamental entity in all these magnetic measurements, has not been studied until recently by the author [6].

All the magnetic measurements require appropriate magnetising circuit (solenoid or EM yoke with suitable ferromagnetic core), with optimum voltage / current applied to the magnetising coil, for externally magnetising the test material. The conventional B-H loop measurement requires a flux coil (for measuring B) and a Hall-effect sensor (for measuring H) in addition to the magnetising circuit. The flux coil output is connected to an amplifier and an integrator to obtain the magnetic induction (B) and plotted against the magnetic field (H). The MBN signal measurement requires an optimised pick-up coil to detect the micro-magnetic flux changes appropriately. As compared to the B-H loop and MBN measurements, the DAME profile measurement is very simple, which requires just the measurement of the voltage across the magnetising coil around the EM yoke (V_E) and calculation of (dV_E/dt). For plotting the V_E (and dV_E/dt) against an independent X-axis, the V_T (total applied voltage at the output of bi-polar power amplifier) can also be easily measured to present a DAME profile (similar to B-H curve and MBN profile) for half the cycle or full cycle of magnetisation.

Recently, for the first time, the distortion analysis of magnetic excitation (DAME) has been shown to distinctly reveal different microstructural states of a ferromagnetic steel by the author [6]. This letter briefly presents the extended work to show that, the simple measurement of DAME profile can reflect subtle variations in ferromagnetic material properties including its stress state and have potential for many other applications such as evaluation of heat-treatment, mechanical processing, fatigue damage, creep damage etc. in ferromagnetic materials.

2. Distortion Analysis of Magnetic Excitation (DAME)

Under a quasi-static triangular waveform excitation condition, the voltage (V_E) applied to an excitation coil of an EM yoke is linearly related to the applied magnetic field strength measured at the centre of air gap between the poles of an EM yoke (in open magnetic flux path). However, in response to Faraday's and Lenz's laws of magnetic induction, the V_E will be distorted, when a ferromagnetic material is placed under the pole faces of the EM yoke (in closed the magnetic flux path), depending on its magnetisation behaviour as explained below.

Incorporating the effect of inductance, the V_E becomes

$$V_E = R_c * i + (N^2 \mu A / l) * (di/dt) + (i N^2 A / l) * (d\mu/dt) \quad (1)$$

and

$$dV_E/dt = R_c * (di/dt) + 2 (N^2 A / l) * (di/dt) * (d\mu/dt) + (i N^2 A / l) * (d^2\mu/dt^2) \quad (2)$$

where 'R_c' is the coil resistance, 'N' is the number of turns in the coil, 'A' is cross-section area of coil, 'i' is the current, 'l' is the length of the coil and 'μ' is the permeability of the magnetic flux path.

It is obvious from equation (1) that, in the presence of another ferromagnetic material introduced to close the magnetic flux path, the V_E is affected by the non-linear magnetisation behaviour of the ferromagnetic material in the flux path through its influence on the magnetic permeability. The distortion in V_E would be very small, making it difficult to clearly distinguish subtle variations caused by different ferromagnetic samples. However, time derivative of V_E is expected to reflect the variations in the magnetisation behaviour of different materials according to equation (2). The plot of (dV_E/dt) as a function of total applied voltage (V_T) (named as the DAME profile) will highlight the distortion behaviour more clearly. This letter, experimentally demonstrates this effect of non-linear distortion of magnetic excitation voltage distinguishing different ferromagnetic materials and the effect of tensile and compressive stress states.

3. Experimental

The experimental set-up for the DAME profile measurement is shown elsewhere [6]. A bi-polar triangular waveform at a frequency of 0.4 Hz is generated which is fed to a bi-polar power amplifier. The alternating voltage output (±20V) of the power amplifier is used to excite the U-shaped iron-core EM yoke (with ~25 mm distance between the poles) connected in series with a current limiting resistor. The magnetic field (~ ±12 kA/m) is applied along the length of the rectangular bar samples. In the DAME profile measurement, the total voltage, V_T, is applied between the excitation coil wound around the core of the EM yoke and a current limiting series resistor (R). Hence, the V_T (typically ±20V in this study) is split into V_E and V_R depending on the values of the resistance of the magnetic excitation coil and the value of the series resistor (R). The V_T, V_R and the V_E are acquired at a sampling rate of 100 kHz over 4 cycles of magnetisation and averaged with a time constant of 5 ms. The V_E is differentiated with dt of 1 ms to obtain (dV_E/dt). The total applied voltage (V_T) is linearly related to the applied magnetic field strength (H_a) measured at the centre of poles of the EM yoke without any

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sample (only air gap), in a half cycle of magnetisation (-V_{Tmax} to +V_{Tmax}). Hence, the DAME profile (dV_E/dt) is plotted as a function of total voltage (V_T) for further analysis.

4. Results and Discussion

Typical variations in V_T, V_R and V_E without any sample and with a ferritic alloy steel sample (Isothermally Annealed –IA) sample) between the poles of the EM yoke are shown below in Fig.1. The V_T is measured at the output of the bi-polar power amplifier which is the sum of V_R and V_E. It can be found from Fig.1 that the V_T, V_R and V_E measured without any sample between the poles of EM yoke vary linearly whilst the V_R and V_E measured with a ferritic steel sample between the poles of the EM yoke vary non-linearly showing the effect of distortion caused by the magnetisation of the ferromagnetic steel between the poles of the EM yoke.

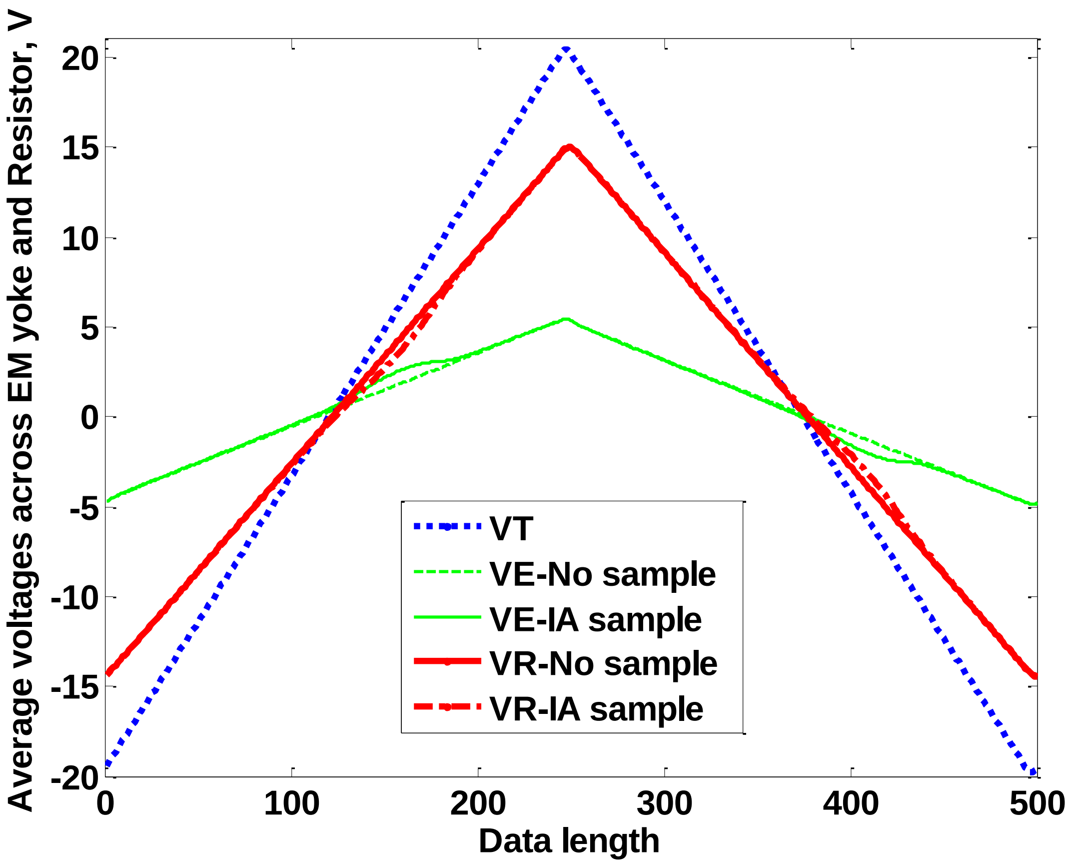

Fig.1. Typical variations in V_T, V_R and V_E (without any sample and with a ferritic steel sample between the poles of the EM yoke) in a cycle. The voltage range of V_E can vary depending on the values of V_T, the magnetising coil resistance and the series resistor (R) used for the measurement. IA denotes the Isothermally Annealed ferritic alloy steel sample placed between the pole of the EM yoke.

In the presence of a ferromagnetic sample, the variation in V_E (Fig.1) deviates with an increase corresponding to the demagnetisation of the sample and then decreases again corresponding to the remagnetisation of the sample in a half cycle of magnetisation (from –V_{Tmax} to + V_{Tmax})

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[6]. Corresponding to this, the DAME ((dV_E/dt) vs V_T) profile shows a peak corresponding to the demagnetisation section and a trough corresponding to the remagnetisation section in a half cycle of magnetisation as shown in Fig.2. This satisfies the effects of Faraday's law / Lenz's law of induction and also shows the effect of magnetisation behaviour of the ferromagnetic material. It can also be realised that the voltage (V_R) drop across the current limiting series resistor (R) in the magnetising circuit will also distort non-linearly in the presence of a ferritic steel samples between the poles of the EM yoke, but in a manner opposite to that of the voltage (V_E) across the EM yoke (Fig.1). That is, in the presence of a ferromagnetic sample, the variation in V_R (Fig.1) deviates with a decrease and then increases again in a half cycle of magnetisation. Corresponding to this, the profile of ((dV_R/dt) vs V_T) will show a trough followed by a peak, opposite to that of the ((dV_E/dt) vs V_T) profile. This is a perfectly balancing effect to support the linearity of the total applied voltage ($V_T = V_R + V_E$) as shown in Fig.1.

As can be observed from Fig.1 that the distortion in V_E is too small to make clear distinction between different samples with subtle variations in properties. However, it has been observed that the time derivative of V_E, the DAME profile (dV_E/dt vs V_T), shows clear distinction between different samples [6]. Typical DAME profile shows a peak and a trough in a half cycle of magnetisation (from $-V_{Tmax}$ to + V_{Tmax}) as shown in Fig.2. Various parameters that can be derived from the DAME profile are: Peak height (P_H), Peak position (P_P), Area of peak profile (P_A), Trough height (T_H), Trough position (T_P), Area of tough profile (T_A), Point of intersection of profiles with and without test material (PoI), Slope between peak and trough (P_s) as defined in Fig.2.

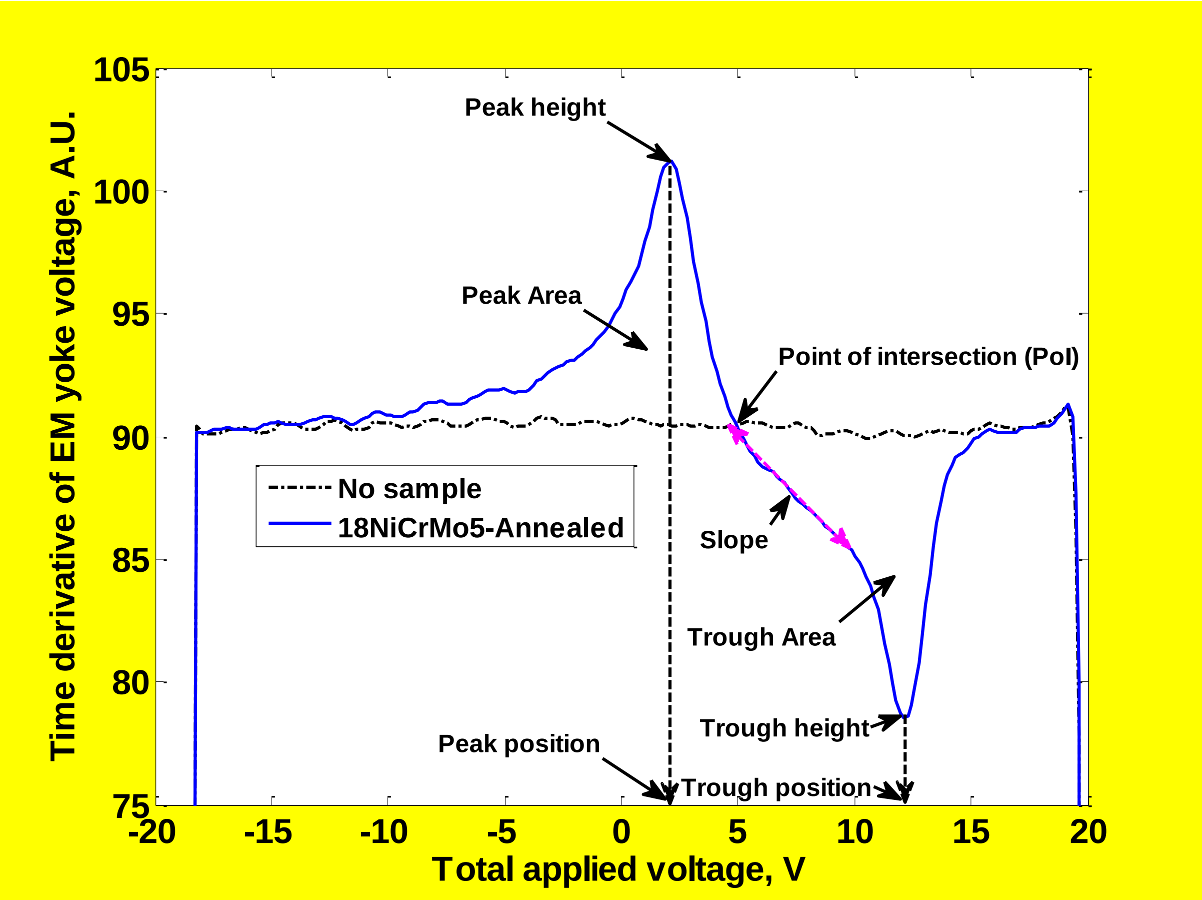

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Fig.2. Typical shape of the DAME profile (dV_E/dt vs V_T) and different parameters that can be derived it for evaluation of ferromagnetic materials.

It is known that the applied magnetic field (H_a) is measured at the centre of air gap (without any ferromagnetic sample) between the poles of EM yoke. In the presence of a ferromagnetic sample between the poles of the EM yoke, only the tangential magnetic field (H_T) can be measured on the surface of the sample. In comparison to the magnetic hysteresis loop measurement, the applied magnetic field (H_a) is directly related to V_T and V_E (measured without any sample between the poles of the EM yoke) in response to the triangular waveform excitation as evident from Fig.1. Similarly, it is expected that, both the H_T and V_E (measured with a ferromagnetic material between the poles of the EM yoke) should show non-linear distortion behaviour and should be related to each other, since both are influenced by the same magnetisation process in the ferromagnetic material between the poles of the EM yoke. The author is currently researching on this aspect.

4.1 Effect of material

The DAME profiles (dV_E/dt vs V_T) obtained without any samples and in the presence of wrought iron, annealed pure Nickel, annealed 18NiCrMo5 alloy steel and quenched and tempered 18NiCrMo5 alloy steel samples between the pole-faces of EM yoke are shown in Fig.3. The DAME profiles are shown only for half the magnetisation cycle ($-V_{Tmax}$ to $+V_{Tmax}$) for better clarity, since it will be symmetrical, but on the negative axis in the other half of the magnetisation cycle ($+V_{Tmax}$ to $-V_{Tmax}$). Figure 4 shows the DAME profiles for Fe-3% Si steel samples in three different grain orientation conditions. It is obvious that the DAME profile is almost linear (constant) without any sample (apart from the sharp changes near the ends which are due to change in the direction of excitation voltage). But, it varies non-linearly when a ferromagnetic sample is placed between the poles. It can also be noticed that the shape of DAME profile (with a peak and a trough) is unique reflecting the property of the ferromagnetic material introduced in the flux path.

More interestingly, in the DAME profile, the section between the descending peak profile and the ascending trough profile shows distinct variations such as single slope or multiple slopes, single peak or two peaks etc. possibly indicating different stages of magnetisation process. The variations in the peak and the trough of the DAME profile reflect the subtle variations in the effect of different material properties (composition, microstructure, stress etc.) on the magnetisation behaviour. Further understanding is required to fully explain the variations (multiple peaks and slopes) in the shape of DAME profile.

The point of intersection (PoI) of DAME ((dV_E/dt) vs V_T) profiles of the test material with that obtained without any sample shows systematic shift with respect to V_T. The PoI should correspond to zero net magnetisation and could be related to coercive force (H_c) of the material. Systematic shift in the point of intersection (PoI) towards increasing V_T clearly indicates the increasing coercive force (H_c) for different materials (Fig.3) as one would expect. More interestingly, Figure 4 clearly shows the effect of grain orientation in Fe-3Si steel. Being the easy magnetisation direction, the grain orientation in <001> direction shows the PoI at lowest V_T and the sample without any grain orientation shows the PoI at higher V_T.

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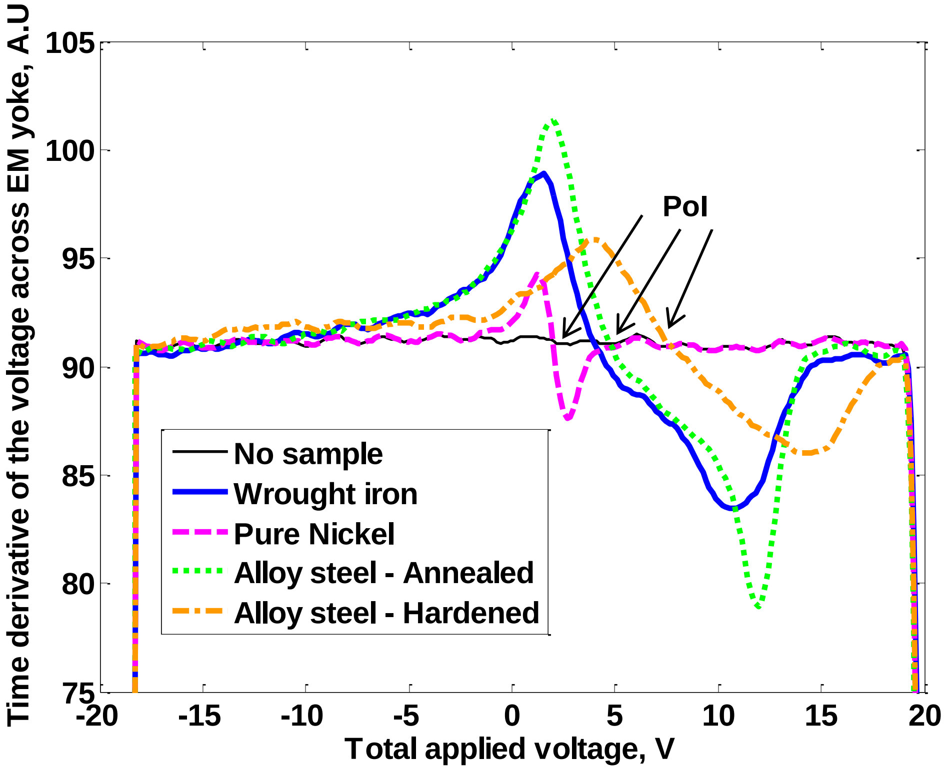

Fig.3. DAME profiles obtained without any sample and with four different ferromagnetic materials between the poles of the EM yoke.

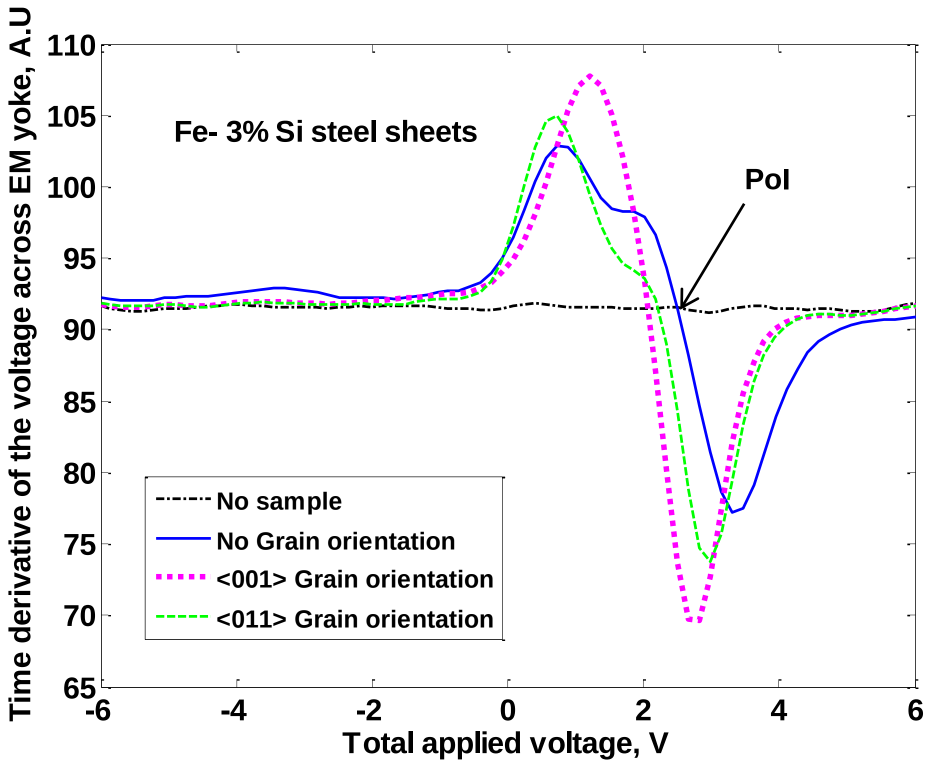

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Fig.4. DAME profiles obtained without any sample and with Fe-3%Si steel samples in three different conditions (The X-axis is limited to ±6V for better clarity).

4.2 Effect of stress

It is well known that the mechanical stresses in the ferromagnetic material affect the magentisation process. This is clearly reflected by the DAME profiles shown in Fig.5(a-b) for an annealed 18CrNiMo5 alloy steel rectangular bar sample subjected to cantilever beam bending to introduce tensile and compressive stresses. Obviously, there is clear difference in the response in the DAME profile between tensile and compressive stresses. The variation in height and position of peak profile for tensile stresses are different to that for compressive stresses. But, the variation in the trough profile appears very similar for both tensile and compressive stresses.

The PoI shows systematic shift to lower V_T for tensile stresses and to higher V_T for compressive stresses as expected in relation to the effect of stresses on coercive force in steels. In addition, the slope (defined in Fig.2) of the section between the peak and the trough shows distinct modification between tensile and compressive stresses. Increase in tensile stress reduces the angle between the descending slope of peak and ascending slope of trough (to develop well-defined 3 slopes) whilst the increase in compressive stress increases that angle making the slope between the peak and the trough as almost linear (single slope). The opposite shift in PoI point for tensile and compressive stresses shows typical effect of stresses in positive magnetostriction materials. The distinct alteration in the slope between the peak and trough profiles indicates the difference in effect of tensile and compressive stresses on magnetisation process. Further studies are required to understand this effect of stress on the DAME profile in more detail.

Since the distortion of V_E (with ferromagnetic material in between the poles of EM yoke) is affected by the rate of change of permeability of the ferritic material in a complex manner (equations 1 and 2), it is difficult to make direct correlation with magnetic induction (B) at present. However, it is possible to compare the B-H curve and the MBN profile with DAME profile to establish the qualitative relationship, which is being pursued by the author. Different ferritic steels have different variations in permeability during the magnetisation process, which depends on the chemical composition, microstructures and stress state in the steel. Hence, the variation in material properties is expected to influence the magnetisation process and hence the shape of the DAME profile. Typical DAME profile parameters such as the position and height of the peak and trough and the point of intersection (PoI) could be correlated to variation in different properties of the ferromagnetic material. Further studies correlating the DAME profile parameters with applied / tangential magnetic field, B-H loop and MBN profile are in progress.

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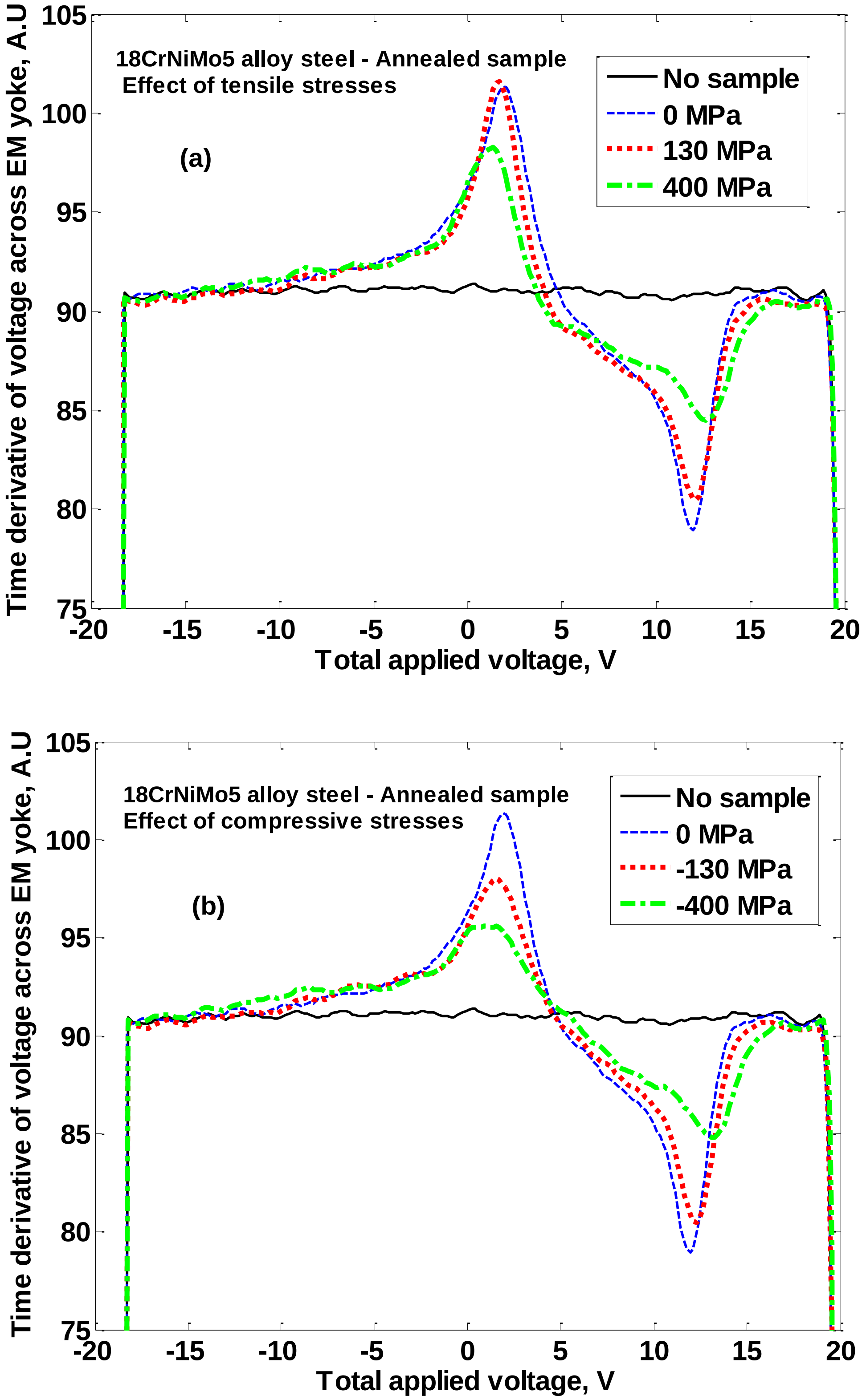

Fig.5. Effect of (a) tensile and (b) compressive stresses on the DAME profiles obtained in 18CrNiMo5 steel annealed bar sample. The shift in point of intersection (PoI) and slope variation can be noticed.

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5. Conclusions

This letter article shows that the non-linear distortion of magnetic excitation voltage (V_E) truly reflects subtle variations in properties of the ferromagnetic material introduced between the poles of the EM yoke. The DAME profile shows unique shape reflecting the differences in the magnetisation process in different ferromagnetic materials. Systematic variations in the DAME profile parameters show that they can be correlated to variations in different properties such as composition, microstructure, grain orientation and stresses influencing the magnetisation process. Further studies are required for systematic understanding of the correlation between DAME profile, other magnetic measurements (B-H loop & MBN) and magnetisation process in different materials.

The DAME is a very simple and faster NDE method (only measuring the V_E across magnetising coil around the EM yoke) as compared to other magnetic measurements. Since the distortion of V_E is expected to be influenced by the magnetisation process over the depth of penetration of the magnetic field strength, it is expected to have larger skin-depth than the MBN and impedance measurements. It may also be possible to vary its skin-depth by varying the frequency of excitation. Hence, this DAME method has potential for various applications such as evaluation of heat treatment, residual stresses, fatigue damage, creep damage, mechanical forming processes etc. in different ferromagnetic materials. Further studies and modelling of the DAME profile would revolutionise this magnetic method for non-destructive evaluation of several ferromagnetic materials and components.

Acknowledgement

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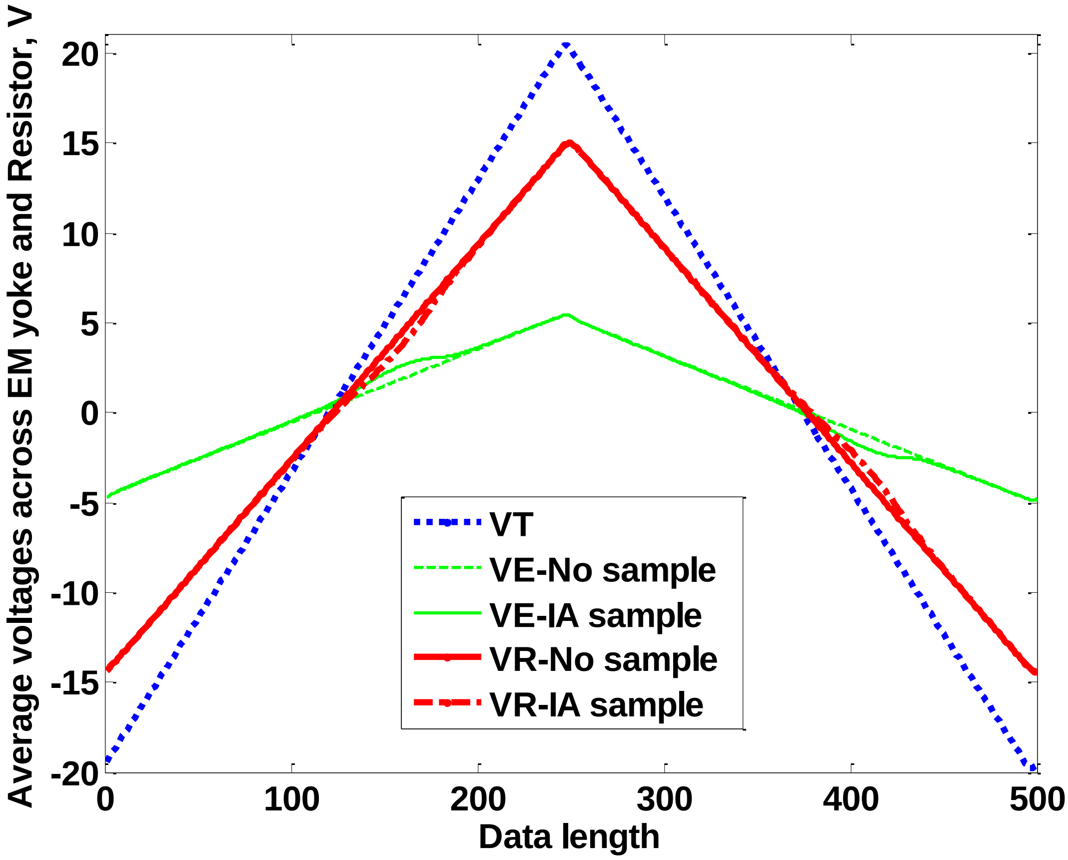
Figures in colour for on-line publication



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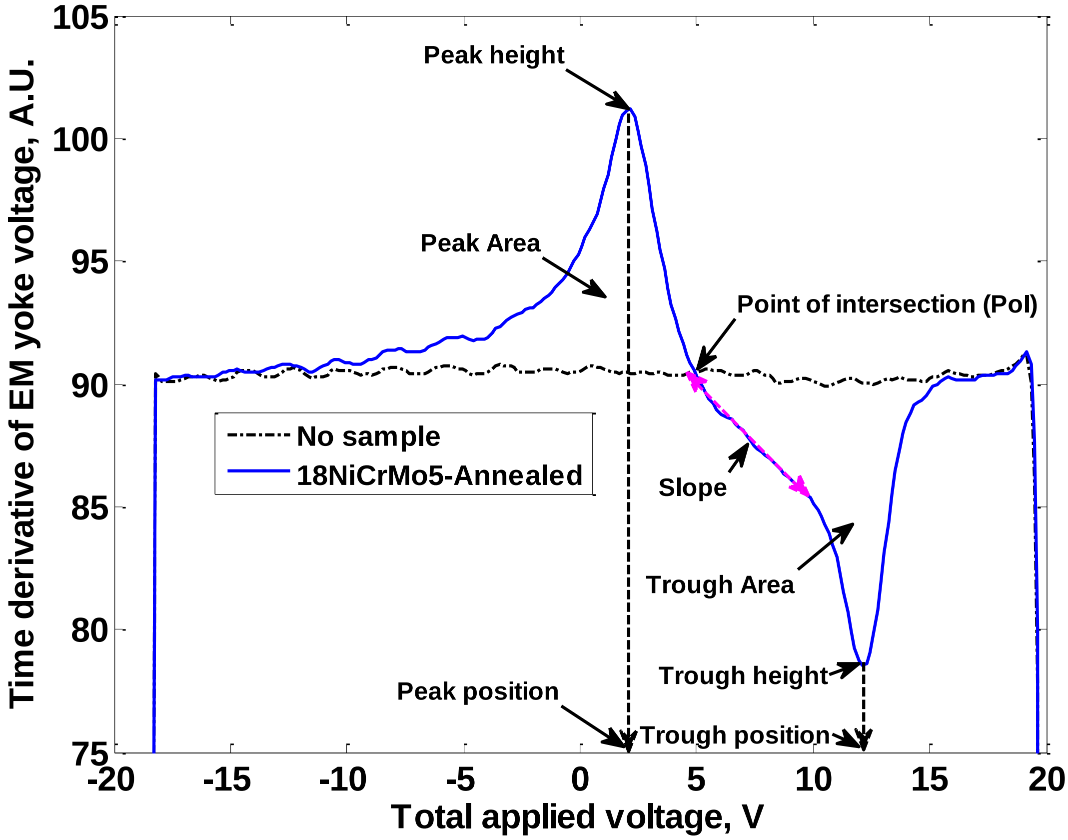

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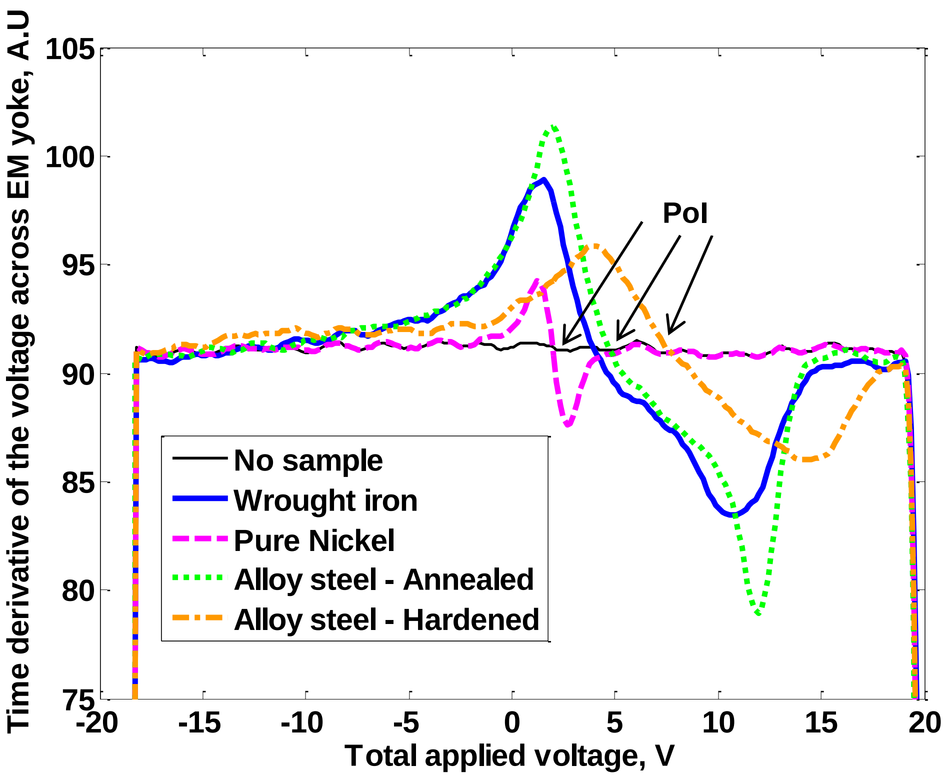

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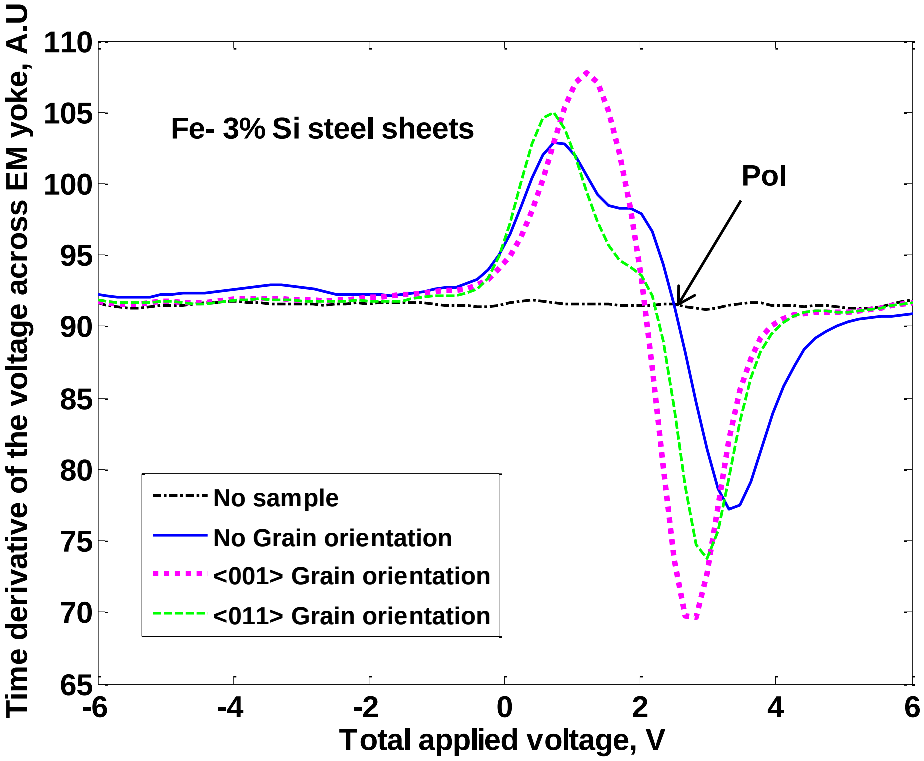

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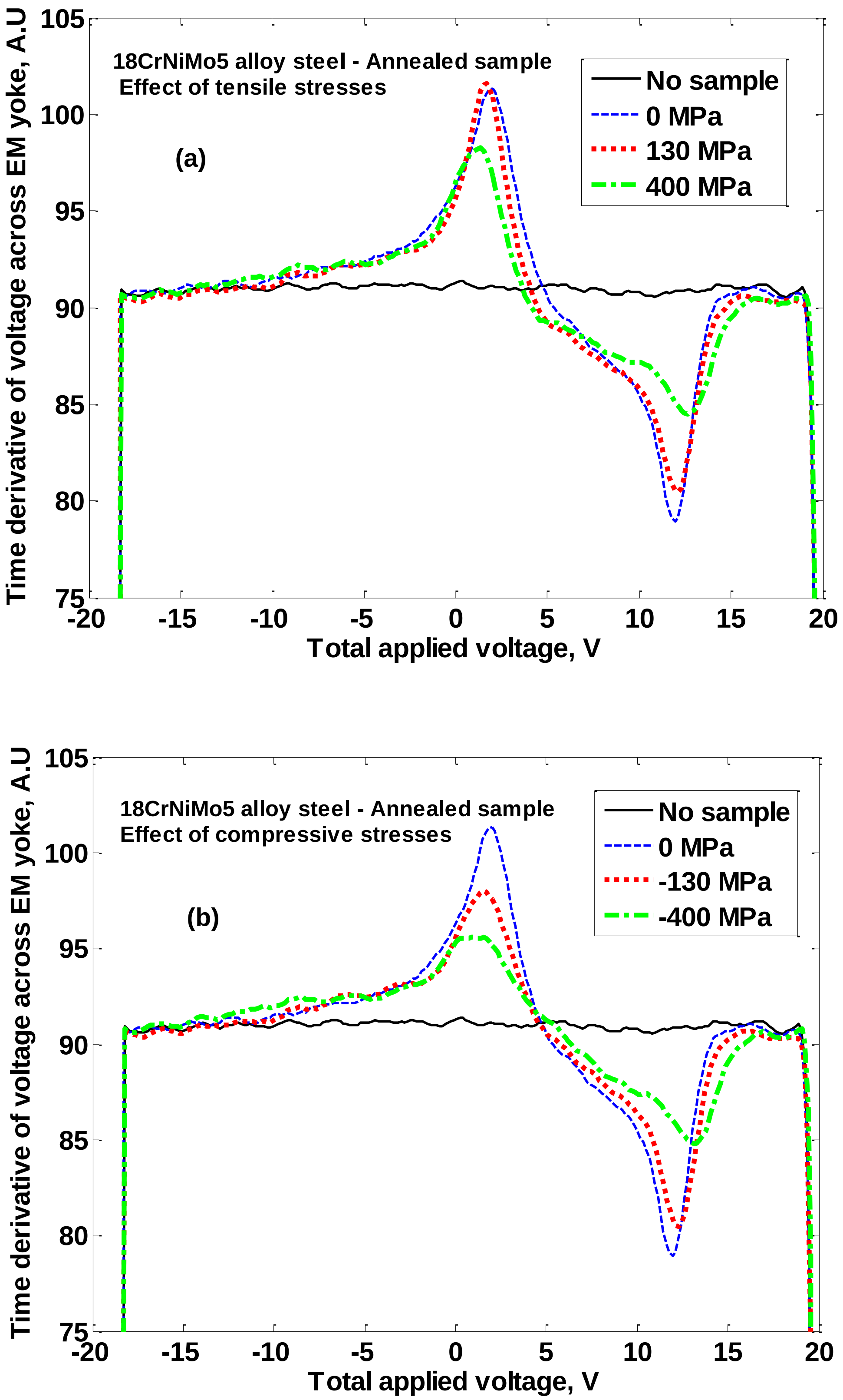

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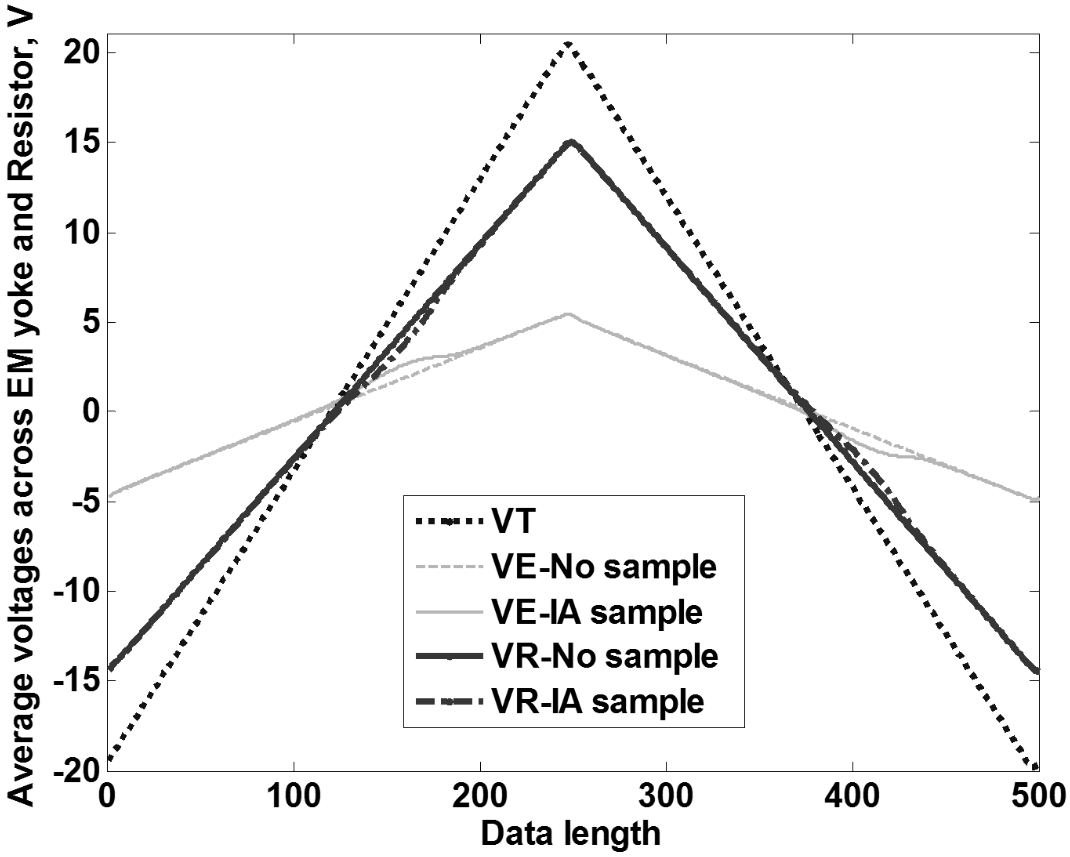

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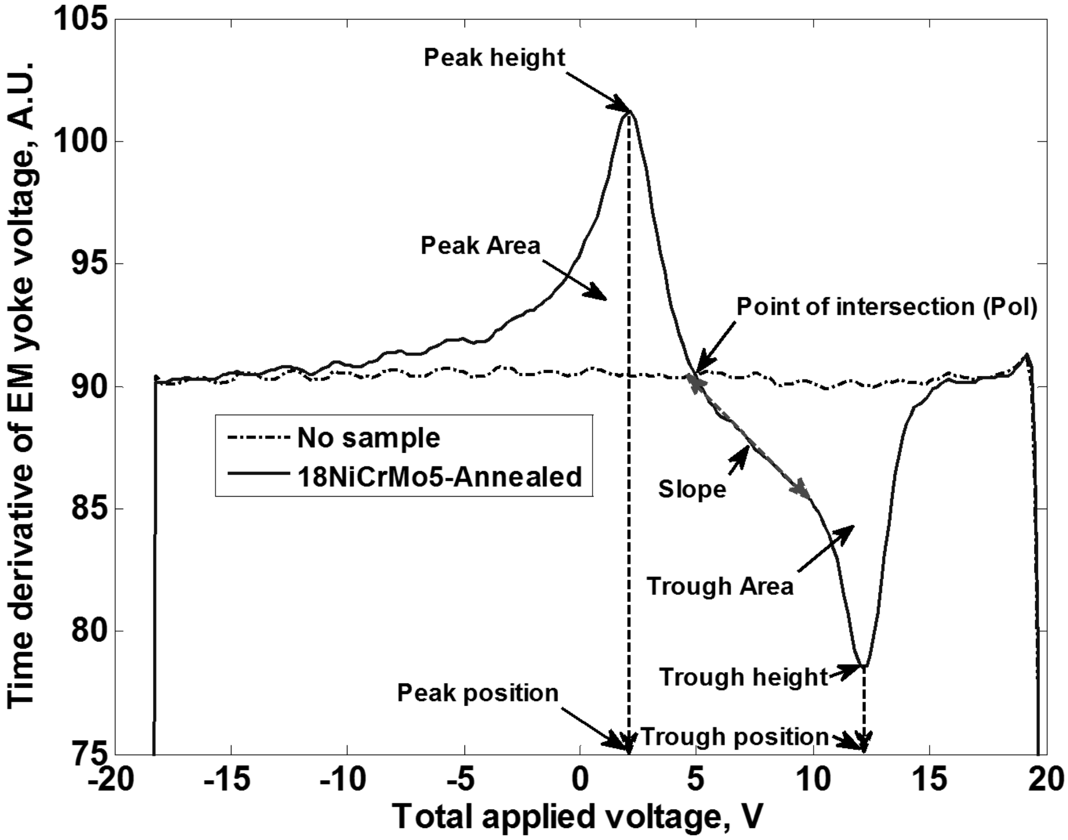

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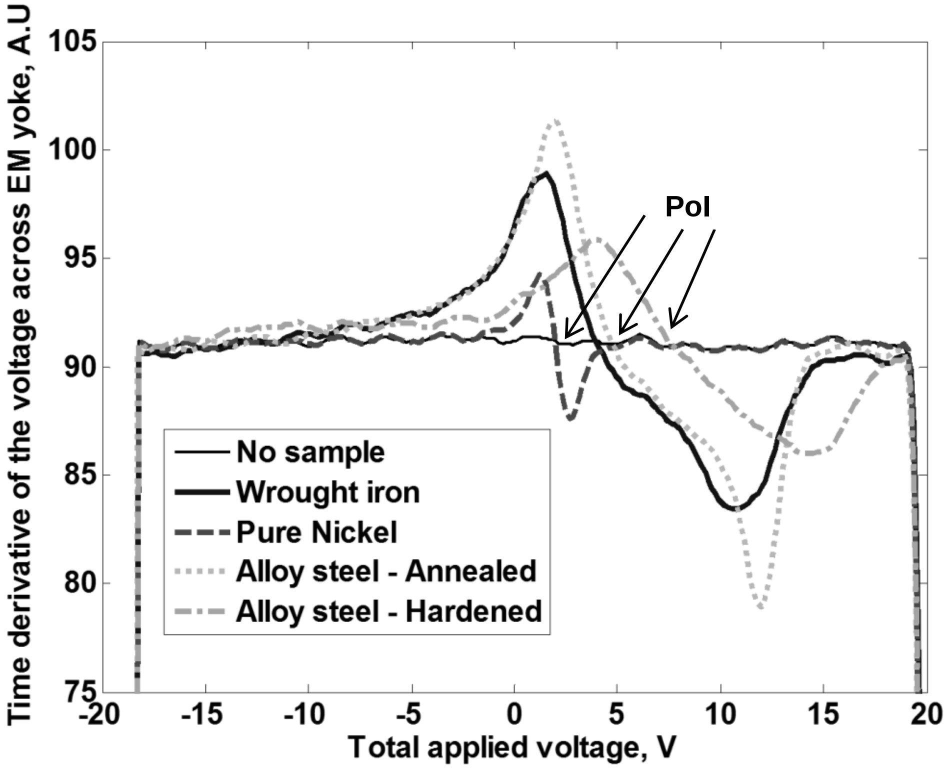

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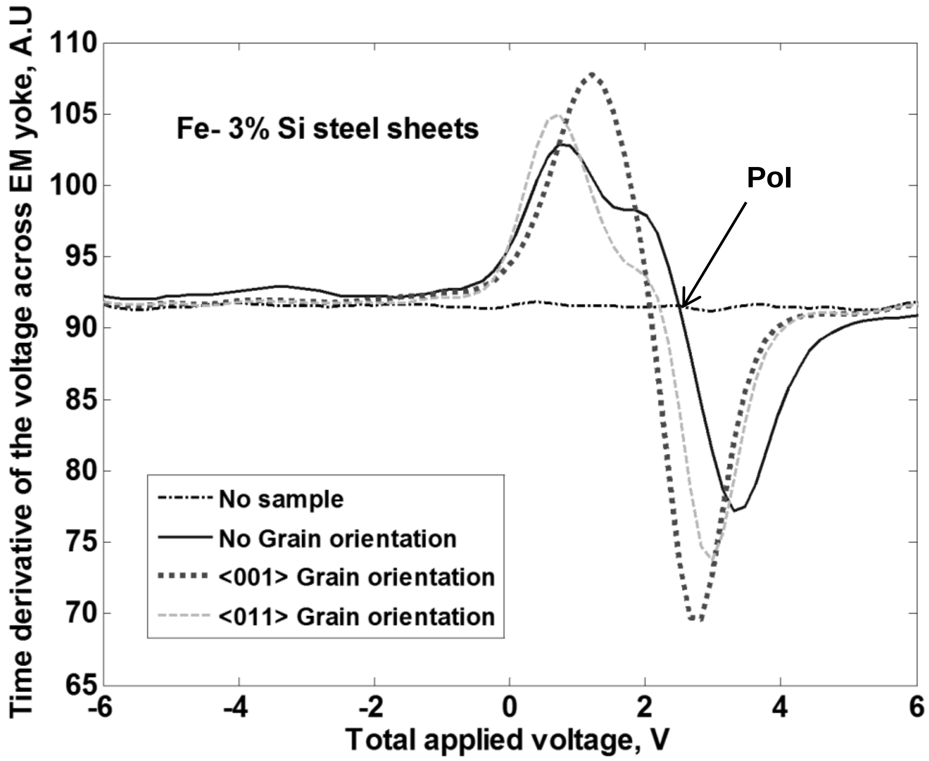

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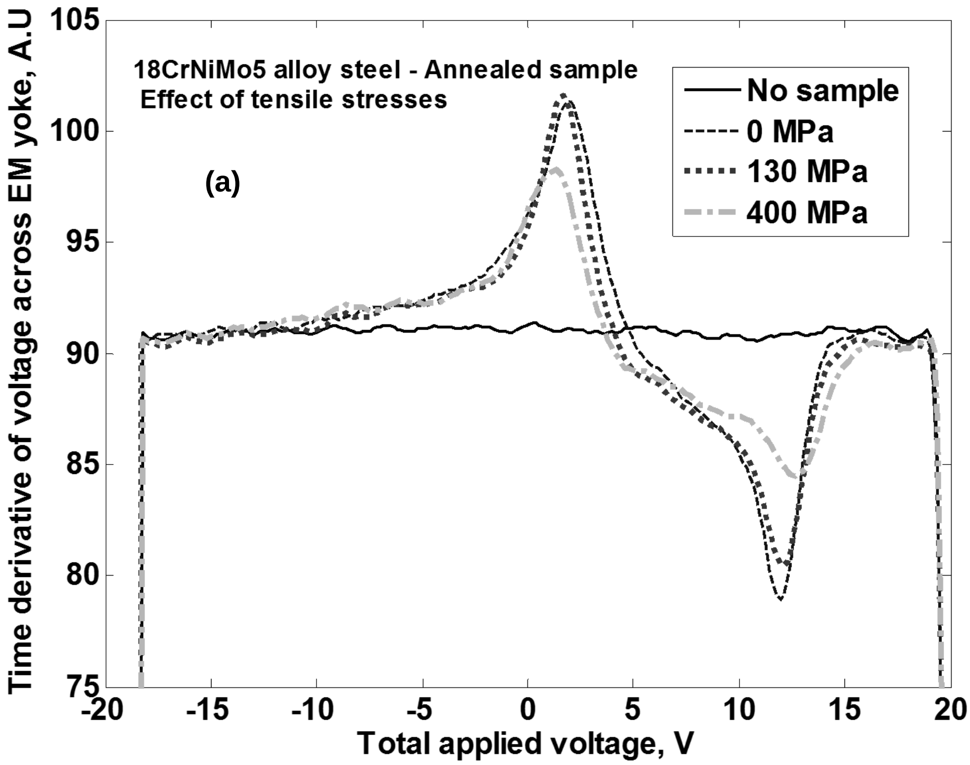

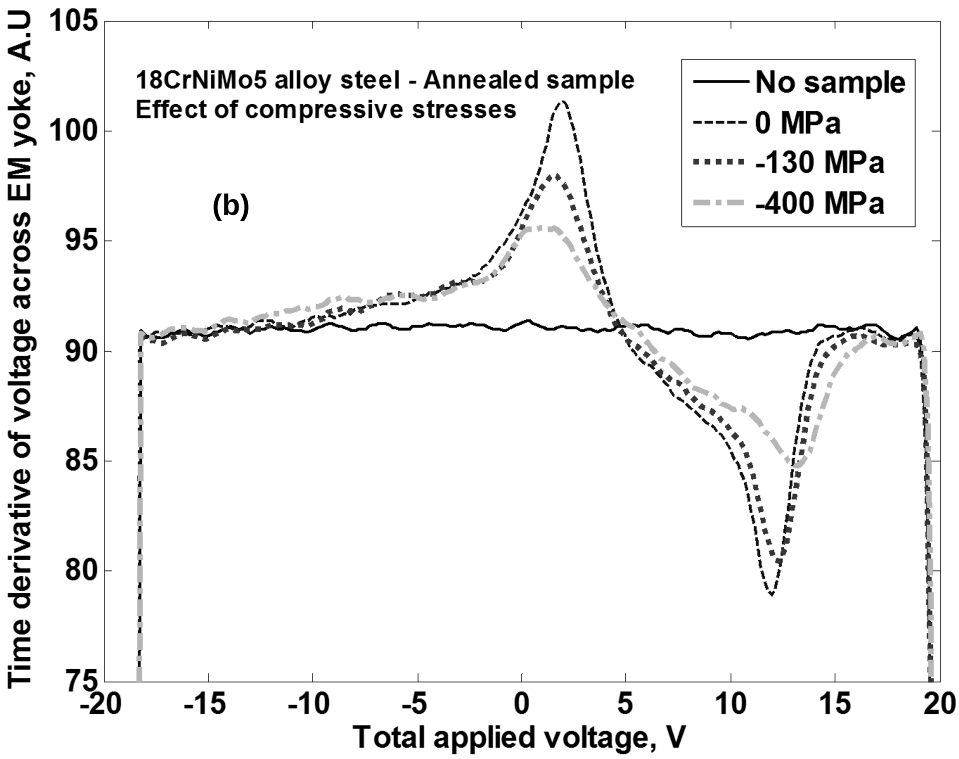

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